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Combined SCAES-ORC, A New Concept of Electricity Storage and Co-generation

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***Abstract*— Subcooled compressed air energy storage (SCAES) technology has newly been introduced. This system stores electricity as compressed air and co-generates heat, cold and electricity as discharging. In this work, it is proposed to use the heat generation potential of the system to drive an Organic Rankine Cycle (ORC) to increase the electrical efficiency of the SCAES. This proposal is modeled, simulated and analyzed. It is well-proved that the combined SCAES-ORC has better electricity and cold production performances about 20% compared to the SCAES system. In addition, due to the heat production of the ORC unit, the heat output of the system is not affected significantly.**

Keywords— Subcooled compressed air energy storage system, Organic Rankine cycle, District heating, District cooling, co-generation

I. INTRODUCTION

Renewable energy technologies will be the main energy suppliers of the future in a 100% extent all around the world [1]. One of the challenges for this transition from the current energy systems to the future absolutely clean energy systems is introducing new tools that are able to address the problems associated with the changeable energy production of some of the main renewable sources such as solar systems and wind turbines [2]. Using energy storage technologies, hybrid renewable technologies, and integrating various energy systems in different energy sectors are the possible solutions for this challenge. The former is, evidently, a primary need among all the possible solutions aforementioned [3].

CAES is one of the many types of electricity storage technologies that have been found as one of the promising storage solutions for the future. The main reason for this is the cost-efficiency of this technology which is better than almost any other mechanical storage technology available in the market and its capability for medium to very large-scale plants [4]. A CAES system in a renewable-based energy system is supposed to use the surplus electricity of solar and wind farms to drive its compressors and produce compressed air at high efficiency. Then, when needed, it generates electricity by expanding the compressed air through its air turbo-generator [5].

Today, there is a variety of CAES designs appropriate for different applications. Diabatic-CAES is the oldest and simplest design of CAES [6]. Then, Adiabatic-CAES design emerged in which the efficiency has been improved by utilizing the heat generation potential of compressors for the air expansion phase [7]. The one-step more advanced design of CAES is Isothermal-CAES which has compressors and expanders in multi-stage designs. This scheme of CAES would result in an overall efficiency of about 80% [8]. Low-temperature-CAES is the next generation of CAES which has lower efficiency compared to the Isothermal-CAES but a simpler design and operation which makes it worth being used in a wide range of specific applications [9]. Finally, SCAES is the newest generation of this technology based on a state-of-the-art [10]. This technology stores electricity just like the previously advanced generation of CAES, i.e. in multi-stage and adiabatic manner. However, the expansion process is unique, where using screw expanders and without any heat supply to the air before expansion, the system co-generates cold and electricity [11]. The overall energy conversion efficiency of this system is about 150% (or a coefficient of performance of 1.5) while the share of electricity efficiency in this is only about 30% which is much less than other CAES designs [12].

On the other hand, it is known that electricity will be the dominant energy sector in the future. Thus, besides solutions for increasing the efficiency of power generation systems, it will be very smart to improve the design of multi-generation systems for higher electricity output rates [13]. For instance, Arabkoohsar and Nami [14] proposed adding an ORC system to a biogas CHP system for increasing the electricity efficiency of the power-heat plant rather than a higher heat efficiency and obtained promising results. Inspired by this work, the current study proposes and thermodynamically investigates adding an ORC unit to a SCAES system so that the heat production of compressors is used for driving the ORC and thereby, generating more electricity.

II. THE HYBRID SCAES-ORC SYSTEM

Figure 1 shows the schematic of the SCAES-ORC system. The combined system comprises the SCAES unit plus the ORC unit. The SCAES system will, naturally, first a charging phase which is followed by a discharging phase when needed. In the charging step, the air is compressed and heat is generated. The compressed air goes to the air reservoir and the heat is gathered to run the ORC unit via its evaporator. This will help the compression process be done at a much higher efficiency as a certain portion of the compressors work is provided by the ORC unit turbine. In addition, much heat is produced via the ORC unit condenser which can be given to the district heating system.

In the discharging step, the compressed air flows through the air turbines and drive the electricity generator. As air is not heated at all before expansion, the airflow will drop to so low temperatures below zero degrees. This means a high cold production potential. Thus, this cold is gathered for supplying district cooling. In the district cooling networks, the supply and return temperatures are about 8 ºC and 15 ºC.

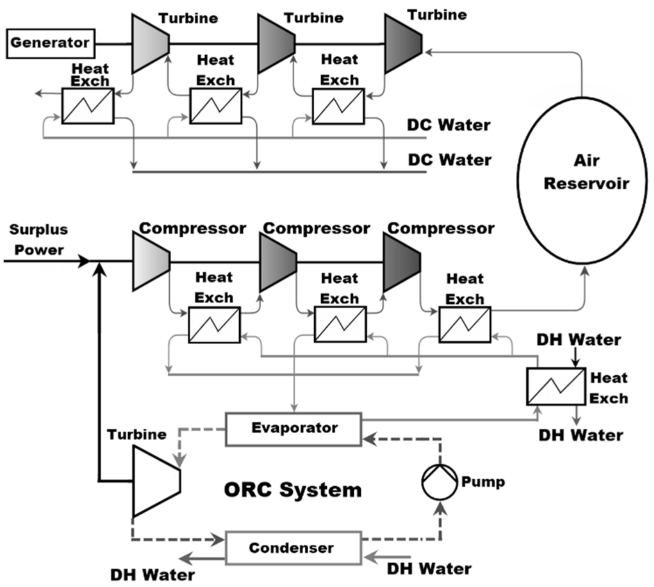

Fig. 1. Schematic of the combined SCAES-ORC system.

III. MATERIAL AND METHODS

For modeling the combined system, two separate operation phases are considered for the system, i.e. charging and discharging. For the former, the compressors, the intercooling heat exchangers, the air reservoir and the ORC unit are in operation. For the compressor set, one has:

$$\dot{W}_c = \dot{E}_s = \sum_{j=1}^{n} (\dot{m}_a w_c)_j \tag{1}$$

where, $\dot{W}_c$, $\dot{m}_a$ and w_c are the total work consumption of the compressors, the airflow rate, and the specific work o the compressor stages, respectively.

For the intercoolers, based on NTU method of heat exchanger modeling, one has:

$$\varepsilon = \frac{1 - \exp\left(-NTU(1 - C_r)\right)}{1 - C_r \exp\left(-NTU(1 - C_r)\right)};$$
$$where:\ NTU = \frac{UA}{C_{min}}\ \&\ C_r = \frac{C_{min}}{C_{max}} \tag{3}$$

where, C is the multiplication of flow rate and heat capacity for the primary and secondary fluids, U is the overall heat transfer coefficient of the heat exchanger, and A is the heat transfer area.

The heat produced by the airflow in this phase and is collected through the intercoolers is calculated by:

$$\dot{Q}_{hx} = \varepsilon C_{min}\left(T_{a,i} - T_{w,i}\right) = \dot{m}_a\left(c_{p,i}T_{a,i} - c_{p,e}T_{a,e}\right) \tag{4}$$

This heat is to be used for driving the ORC unit. Thus, for the evaporator of the ORC, one has:

$$\dot{m}_w\left(h_{w,i} - h_{w,e}\right) = \dot{m}_{MM}\left(h_{MM,e} - h_{MM,i}\right) \tag{7}$$

MM is the organic working fluid chosen for the ORC unit in this work and h refers to the enthalpy of the flows. Considering the pressure of the ORC condenser as 1.05 bar, and the ORC turbine isentropic efficiency as 0.85, the properties of MM at the ORC condenser inlet are calculated. Having this, one may calculate the work of the ORC turbine as well:

$$h_{MM,e} = h_{MM,i} - \eta_{is,orc-t}\left(h_{MM,i} - h_{MM,es}\right);$$
$$\text{Where: } h_{MM,es} = h_{MM}|_{P=1,750\ kPa,\ \ x=1} \tag{8}$$

$$\dot{W}_{orc-t} = \dot{m}_{MM}\left(h_{MM,i} - h_{MM,e}\right) \tag{9}$$

The ORC condenser supports district heating in which the return line is 40 °C and should be heated up to 80 °C [15]. For the ORC condenser, one may write:

$$\dot{m}_{MM}\left(h_{MM,i} - h_{MM,e}\right) = \dot{m}_{dh}\left(h_{dhs} - h_{dhr}\right);$$
$$\text{Where: } h_{MM,e} = h_{MM}|_{P=105\ kPa,\ \ x=0} \tag{10}$$

In which, *hd*, *dhs,* and *dhr* represent district heating, and its supply and return lines, respectively.

For the ORC pump, the following equation applies:

$$\dot{W}_{orc-p} = \dot{m}_{MM}\left(h_{MM,i} - h_{MM,e}\right) = \dot{m}_{MM}\upsilon_{MM}\left(P_{MM,i} - P_{MM,e}\right) \tag{11}$$

here, P and υ are pressure and the specific volume of the MM.

As such, for the extra heat exchanger after the evaporator exit, which supports further district heating, one has:

$$\dot{m}_w\left(h_{w,i} - h_{w,e}\right) = \dot{m}_{dh}\left(h_{dhs} - h_{dhr}\right) \tag{12}$$

The pressure of the air reservoir changes as:

$$P_{cr}^{\lambda} = \left(\frac{m_{cr}RT_{cr}}{V_{cr}}\right)^{\lambda} \tag{13}$$

in which, $m_{cr}^{\lambda} = m_{cr}^{\lambda-1} + \dot{m}_a$ and $T_{cr} = T_{am}$, *cr* is the storage volume, λ is the time-step counter, and V_{cr} and m_{cr} are the volume and mass of the reservoir.

In the discharging step, the air turbines, the heat exchangers between them and the air reservoir are operating. the total work produced by the turbines is calculated by:

$$\dot{W}_t = \frac{\dot{E}_d}{\eta_g} = \sum_{j=1}^{n} (\dot{m}_a w_t)_j \tag{14}$$

in which, $\dot{E}_d$ and η_g are the amount of electricity needed to be generated and the efficiency of the electricity generator (assumed as 0.98 here). The specific work of turbines could be calculated by the following formula:

$$w_t = RT_i \frac{\mu}{\mu - 1}\left(\frac{1 - r_t^{\left(\frac{k-1}{k}\right)}}{\eta_{is,t}}\right) \tag{15}$$

The cold energy generated by in airflow and collected by the heat exchangers between the turbines is calculated by:

$$\dot{Q}_{cold} = \sum_{j=1}^{n} \left(\dot{m}_{dc}(T_{dcr} - T_{dcs})\right)_j \tag{16}$$

The air reservoir pressure in this phase is given by:

$$P_{cr}^{\lambda} = \left(\frac{m_{cr}RT_{cr}}{V_{cr}}\right)^{\lambda} \quad \boldsymbol{where}: m_{cr}^{\lambda} = m_{cr}^{\lambda-1} - \dot{m}_a \tag{17}$$

In the end, he efficiencies of the combined system defined as heat-efficiency, cold-efficiency, and electrical-efficiency are given by:

$$\eta_{pth} = \sum_{\lambda=1}^{tc} \left(\frac{\dot{Q}_{dh}}{\dot{E}_s - \dot{W}_{orc-t}}\right)^{\lambda} \tag{18}$$

$$\eta_{ptc} = \frac{\sum_{\lambda=1}^{td} \dot{Q}_{dc}^{\lambda}}{\sum_{\lambda=1}^{tc}(\dot{E}_s - \dot{W}_{orc-t})} \tag{19}$$

$$\eta_{ptp} = \frac{\sum_{\lambda=1}^{td} \dot{E}_d^{\lambda}}{\sum_{\lambda=1}^{tc}(\dot{E}_s - \dot{W}_{orc-t})} \tag{20}$$

The summation of these three efficiencies gives the overall coefficient of performance of the combined cycle as:

$$COP = \frac{\sum_{\lambda=1}^{td} \dot{E}_d^{\lambda} + \sum_{\lambda=1}^{td} \dot{Q}_{dc}^{\lambda} + \sum_{\lambda=1}^{tc} \dot{Q}_{dh}^{\lambda}}{\sum_{\lambda=1}^{tc}(\dot{E}_s - \dot{W}_{orc-t})} = \eta_{pth} + \eta_{ptp} + \eta_{ptc} \tag{21}$$

here, *tc* is the total number of charging time-steps and *td* represents the same for the discharging phase.

IV. Results and Discussion

For simulating the system behavior under changeable conditions, it is supposed here that the combined SCAES-ORC is connected to a wind turbine. Figure 2 gives information about the excess electricity of the wind turbines (scaled to the peak value of 5 MW) for 12 continuous hours. This is going to be used for charging the storage system.

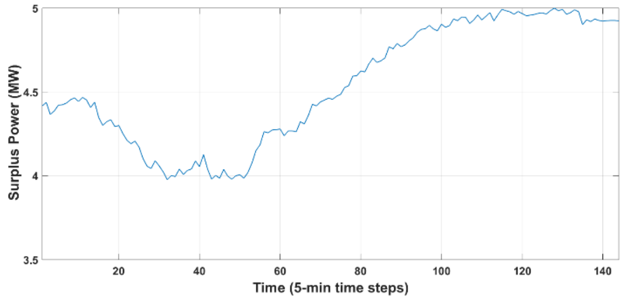

Fig. 2. Surplus electricity of the wind turbine in 12 hours (5-min time-steps).

Figure 3 gives information about the amount of electricity that should be generated by the storage unit in the second 12-hour period, which is the discharging mode of the plant. Here also, the maximum required electricity is scaled to 5 MW.

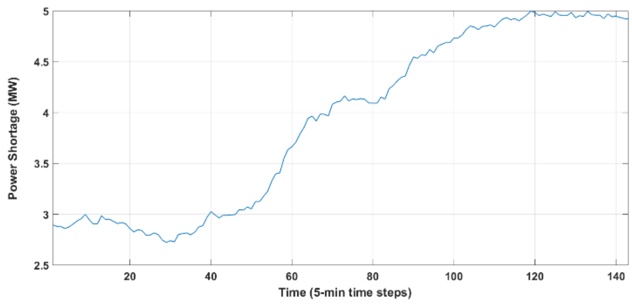

Fig. 3. Rate of the surplus electricity demand of the wind turbine for 12 hours.

Figure 4 shows which flow rate of compressed air is produced by the compression stage during each time step and what amount of airflow needs to be expanded to cover the demanded electricity of the wind turbine.according to the figure, compressed air production flow rate changes between 17 kg/s as the lowest value over the 12 charging hours and the peak value of 22 kg/s. the mass flow rate of the expanded air varies within the range 40 kg/s to 60 kg/s for the times the air reservoir has not been fully discharged and then it drops to zero as there is no more excess compressed air within the reservoir to be discharged.

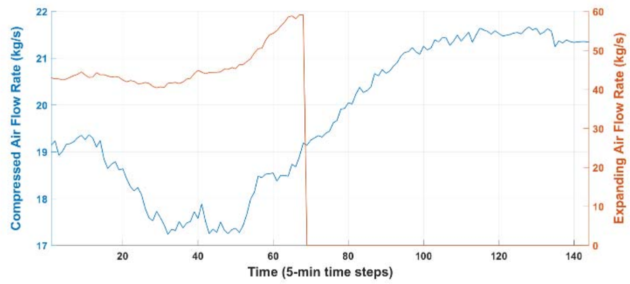

Fig. 4. Compression and expansion flow rate of air in the combined system.

Figure 5 presents information about the rate of heat supply for district heating by the ORC condenser and the extra heat exchanger after the ORC evaporator. As seen, the ORC condenser contribution is almost three times larger than the extra heat exchanger for district heating support, though the latter is still considerable with a minimum supply rate of 1.1 MW and maximum support of about 1.4 MW.

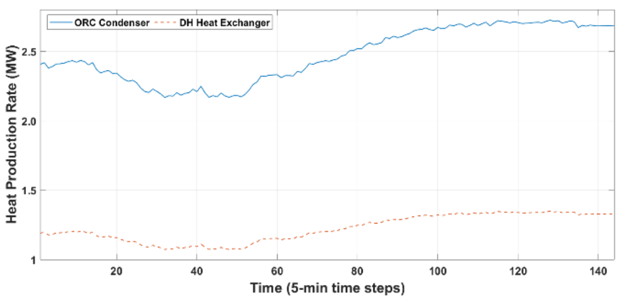

Fig. 5. Heat production rate for district heating.

Figure 6 shows the rate of cold production of the system. This parameter is so close to the rate of electricity production. The electricity production of the system is, naturally, on the same trend as that presented in Figure 3 until the air reservoir is discharged thereafter the electricity and cold production both ill drop to zero.

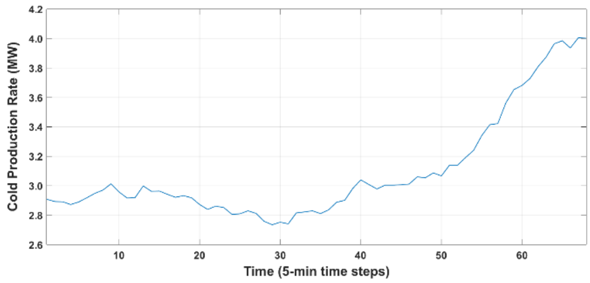

Fig. 6. Rate of cold production of the SCAES system when discharging.

Finally, Figure 7 presents information about the efficiency indices of the system (cold, heat, electrical and overall efficiencies) before and after implementing the proposed combination. As seen, not only the electrical efficiency of the system increases from 30% to over 36%, its cold efficiency is improved and its heat efficiency is not destroyed. Thus, the overall efficiency is also improved.

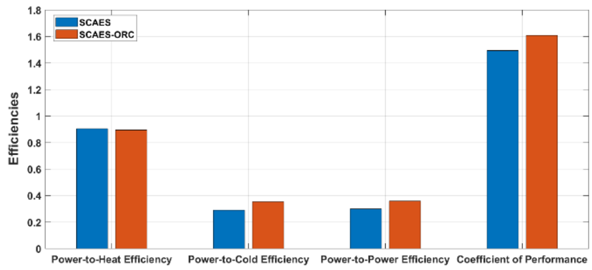

Fig. 7. Efficiencies in the SCAES system and the combined SCAES-ORC system.

V. CONCLUSION

In this work, the combination of a SCAES system, which is a new generation of CAES technologies in the category of mechanical energy storage systems, with an ORC unit was proposed and analyzed.

The main aim of the proposal was to increase the electrical efficiency of the SCAES system, no matter what happens to its cold and heat efficiencies as electricity is going to be a significantly more important energy flow in the future. The results, however, showed that the proposed combination not only increases the electrical efficiency for more than 20% but also the cold production efficiency is improved for the same rate. In addition, the heat production capacity of the storage system is not affected significantly, and this is why the overall energy efficiency of the cycle is also improved.

REFERENCES

[1] E. O'Dwyer, I. Pan, S. Acha, N. Shah, Smart energy systems for sustainable smart cities: Current developments, trends and future directions, Appl Energy. 237 (2019) 581–597. doi:https://doi.org/10.1016/j.apenergy.2019.01.024.

[2] M. Sadi, A. Arabkoohsar, M. Sadi, A. Arabkoohsar, Modelling and Analysis of a Hybrid Solar Concentrating-Waste Incineration Power Plant, J Clean Prod. (2018). doi:https://doi.org/10.1016/j.jclepro.2018.12.055.

[3] C. Prieto, P. Cooper, A.I. Fernández, L.F. Cabeza, Review of technology: Thermochemical energy storage for concentrated solar power plants, Renew Sustain Energy Rev. 60 (2016) 909–929. doi:https://doi.org/10.1016/j.rser.2015.12.364.

[4] A. Arabkoohsar, L. Machado, R.N.N. Koury, K.A.R. Ismail, Energy consumption minimization in an innovative hybrid power production station by employing PV and evacuated tube collector solar thermal systems, Renew Energy. 93 (2016) 424–441. doi:https://doi.org/10.1016/j.renene.2016.03.003.

[5] A. Arabkoohsar, L. Machado, R.N.N. Koury, Operation analysis of a photovoltaic plant integrated with a compressed air energy storage system and a city gate station, Energy. 98 (2016) 78–91. doi:10.1016/j.energy.2016.01.023.

[6] B. Elmegaard, W. Brix, Efficiency of compressed air energy storage, Proc 24th Int Conf Effic Cost, Optim Simul Environ Impact Energy Syst ECOS 2011. (2011) 2512–2523.

[7] S. Tong, Z. Cheng, F. Cong, Z. Tong, Y. Zhang, Developing a grid-connected power optimization strategy for the integration of wind power with low-temperature adiabatic compressed air energy storage, Renew Energy. 125 (2018) 73–86. doi:https://doi.org/10.1016/j.renene.2018.02.067.

[8] A. Odukomaiya, A. Abu-Heiba, K.R. Gluesenkamp, O. Abdelaziz, R.K. Jackson, C. Daniel, S. Graham, A.M. Momen, Thermal analysis of near-isothermal compressed gas energy storage system, Appl Energy. 179 (2016) 948–960. doi:https://doi.org/10.1016/j.apenergy.2016.07.059.

[9] D. Wolf, M. Budt, LTA-CAES – A low-temperature approach to Adiabatic Compressed Air Energy Storage, Appl Energy. 125 (2014) 158–164. doi:https://doi.org/10.1016/j.apenergy.2014.03.013.

[10] A. Arabkoohsar, M. Dremark-Larsen, R. Lorentzen, G.B. Andresen, Subcooled compressed air energy storage system for coproduction of heat, cooling and electricity, Appl Energy. 205 (2017) 602–614. doi:10.1016/j.apenergy.2017.08.006.

[11] A. Arabkoohsar, An Integrated Subcooled-CAES and Absorption Chiller System for Cogeneration of Cold and Power, in: 2018 Int Conf Smart Energy Syst Technol, 2018: pp. 1–5. doi:10.1109/SEST.2018.8495831.

[12] A.S. Alsagri, A. Arabkoohsar, H.R. Rahbari, A.A. Alrobaian, Partial Load Operation Analysis of Trigeneration Subcooled Compressed Air Energy Storage System, J Clean Prod. (2019) 117948. doi:https://doi.org/10.1016/j.jclepro.2019.117948.

[13] A. Arabkoohsar, H. Nami, Thermodynamic and economic analyses of a hybrid waste-driven CHP–ORC plant with exhaust heat recovery, Energy Convers Manag. 187 (2019) 512–522. doi:https://doi.org/10.1016/j.enconman.2019.03.027
.

[14] H. Nami, A. Arabkoohsar, A.A. H. Nami, Improving the Power Share of Waste-Driven CHP Plants via Parallelization with a Small-Scale Rankine Cycle, a Thermodynamic Analysis, Energy. In Press (2019) 27–36. doi:10.1016/j.energy.2018.12.168.

[15] A. Arabkoohsar, G.B.B. Andresen, Design and analysis of the novel concept of high temperature heat and power storage, Energy. 126 (2017) 21–33. doi:10.1016/j.energy.2017.03.001.